MSFC-220

ICONIC 2007
St. Louis, MO, USA
June 27-29, 2007

ON THE MUTUAL COUPLING BETWEEN CIRCULAR RESONANT SLOTS

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Abstract. For near- and far-field microwave imaging purposes, array of circular resonant slots can be utilized to sample the electric field at a given reference plane. In general, the sensitivity of such an array is impaired by the existing mutual coupling between the radiating elements or in this case circular slots. The mutual coupling problem imposes a design tradeoff between the resolution of the array and the overall system sensitivity and dynamic range. In this paper, the mutual coupling between circular resonant slots in conducting ground plane is investigated both numerically and experimentally. In particular, the mutual coupling in the E- and H-plane configurations of two identical slots is studied.

Keywords: circular resonant slots, mutual coupling, surface currents

1 INTRODUCTION

Slots in conducting ground planes are attractive elements that may be used in imaging antenna arrays. Since they are easy to manufacture and possess a low profile as a flush-mounted antenna, such arrays are widely utilized in many applications [1]. Near- and far-field high resolution imaging probes can also be realized using slot arrays. The shape, size, and configuration of the array are design parameters which typically depend on the required detection sensitivity and spatial resolution.

Circular resonant slots, although not as commonly used as rectangular slots, are potential candidates for the construction of the imaging probes. A circular resonant slot is basically a circular slot in which conducting strips are extended from the ground plane and routed within the slot area. The conducting strips should be routed such that they add an appropriate capacitive load to the inductive circular slot [2]. The shape and size of the routed strips dictates the resonant frequency.

For high resolution imaging applications, large arrays of closely spaced circular resonant slots can be arranged to sample the electric field at a given reference plane. The reason behind using circular resonant slots for the construction of the imaging arrays is multifold. The high sensitivity associated with a circular slot at its resonant frequency and its small physical size are major advantages over other elements, e.g., rectangular slots. Consequently, better sampling of the field can be achieved using sub-half-wavelength slots interspacing. However, the mutual

coupling among the slots can severely impact the sensitivity of the imaging system. Hence, the need arises to study and reduce the mutual coupling between this type of slots.

Mutual coupling between rectangular slots in a conducting plane and coupling reduction techniques have been studies extensively (see [3] and the references therein). However, mutual coupling between resonant circular slots has not been similarly addressed in past. This is mainly due to the complexity of their shapes. However, with the advancement in numerical modeling techniques the interaction between circular resonant slots can be analyzed using commercially available software packages such as Ansoft's HFSS® [4]. In this paper, the mutual coupling between two identical circular slots is investigated both numerically and experimentally. HFSS® is used to numerically model the single and coupled slots cases. The analysis show that the coupled power reduces exponentially with interspacing between the slots.

2 DESCRIPTION AND APPROACH

The resonant circular slot of interest here is similar to a waveguide iris that is commonly used to couple the cavity of Gunn oscillators to waveguide sections, as shown in Fig. 1(a). The circular resonant slot construction is based on loading an inductive circular slot by a capacitive load. As shown in Figure 1(a), the capacitive load is added via the gap between the conducting strips. For thin ground planes, the capacitance of the gap is mainly controlled by changing the length of the gap. Increasing the gap length has the effect of decreasing the resonant frequency, and vice versa. For slot diameter of $\lambda/4$ and with a gap length of 0.46 mm, the slot is expected to resonate around the center of the X-band frequency range (8.2-12.4 GHz).

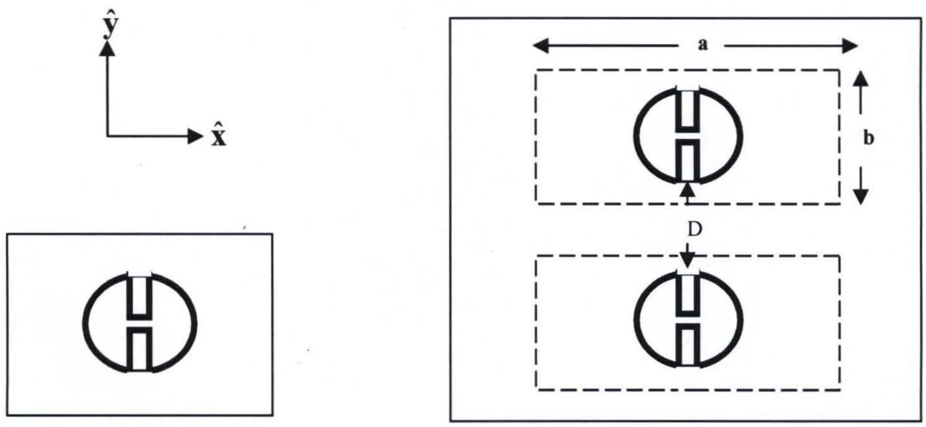
The interaction between two identical circular resonant slots fed by apertures of rectangular waveguides as depicted in Figure 1(b) is considered herein. Such arrangement is referred to as E-plane arrangement where the edge-to-edge interspacing between the slots is D. The H-plane arrangement is 90°-rotated version of the E-plane arrangement.

The single slot response and the mutual coupling between two adjacent slots were measured using a Vector Network Analyzer (VNA), i.e., HP8510C, in the X-band frequency range. For the coupled slots case, calibrated scattering parameters referenced at the feeding waveguide apertures were measured. Subsequently, the single slot response and the mutual coupling were computed using HFSS and compared to the measurements.

3 RESULTS

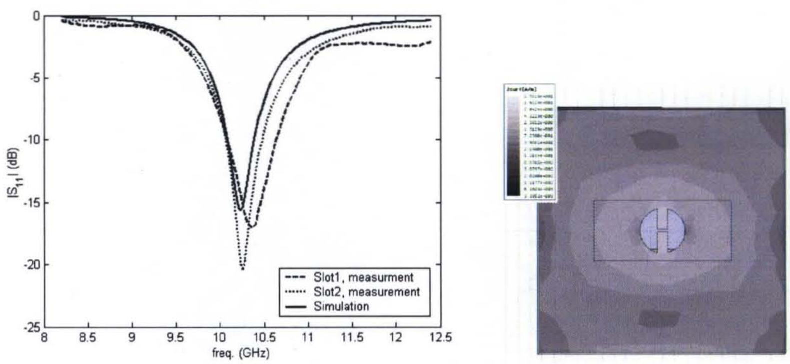
Figure 2(a) shows the simulated and measured response, S_{11}, of two $\lambda/4$-diameter circular isolated resonant slots with air gap length of 0.46 mm. As shown in Figure 2(a), the resonance frequency is around 10.24 GHz. Clearly, there is a good match between the measurements and simulations results. To study the radiation characteristics of this type of slots, the surface current density was also computed as depicted Figure 2(b). The current is large along the conducting strips, and it spreads asymmetrically outside the slot area. Actually, it is observed that the current is larger along axis of the conducting strips, i.e., y-axis, compared to orthogonal axis. This will

dictate a certain mutual coupling behavior when two slots are arranged on the y-axis (E-plane) and x-axis (H-plane) as it will shown next.



(a) (b)

Figure 1: (a) A circular resonant slot, (b) two-element E-plane array of two waveguide-fed circular resonant slots.



(a) (b)

Figure 2: (a) simulated and measured response of two circular resonant slots, and (b) the surface current density (dB) for a single isolated slot.

For the coupled slots, the scattering parameters were computed in the X-band frequency range for the E- and H-plane slot cases with D =34 mm. Subsequently, the simulation results were compared to the measurements obtained for these arrangements. Figure 3 shows the measured coupling coefficient, $|S_{21}|$, in dB as function of frequency for both E- and H-plane cases.

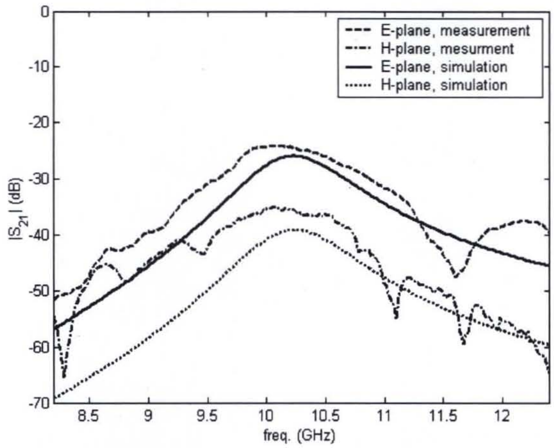
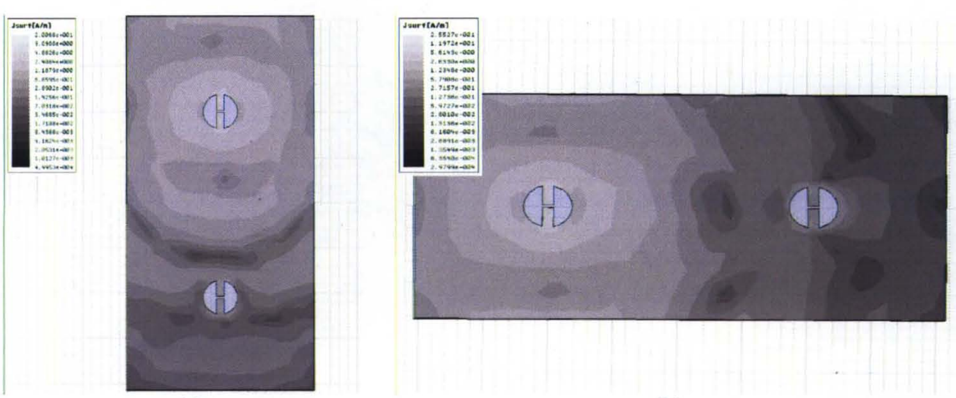


Figure 3: Computed and measured $|S_{21}|$, in dB as function of frequency for both E- and H-plane cases for $D = 34$ mm.

In general, the E-plane measurements matched their simulation counterparts better than the H-plane measurements. At the resonant frequency, however, a good agreement between measurement and simulations is shown for both cases. It is evident that the E-plane coupling coefficient is at least 10 dB higher than the value obtained for the H-plane case. This is mainly attributed to fact that the surface current density at the location of the coupled slot for the E-plane (coupled slot is along the y-axis) case is larger compared to the H-plane case (coupled slot is along the x-axis), as mentioned previously. To verify this fact, the surface current densities for the E- and H- plane coupled slots at 10.24 GHz when one of the slots is not transmitting were computed as shown in Figure 4.



(a) (b)

Figure 4: The surface current density (dB) for the coupled slots at 10.24 GHz when one slot is not transmitting; (a) E-Plane and (b) H-plane.

The surface current induced on the non-transmitting slot due to the transmitting one for the E-plane case (Figure 4(a)) is shown to be larger compared to the H-plane case (Figure 4(b)). Consequently, the coupling coefficient for the E-plane case is larger.

Finally, the effect of the slots interspacing, D, on the mutual coupling between them was investigated. Figure 5 shows the normalized coupling coefficient between the slots for the E-plane case as a function of normalized interspacing (the H-plane will be around 10 dB less). The normalized coupling coefficient was computed as:

$$C = 10\log\left[\frac{|S_{12}|^2}{(1-|S_{11}|^2)(1-|S_{22}|^2)}\right] \quad \text{(dB)}$$

where S_{11}, S_{12}, and S_{22} are the scattering parameters computed at 10.24 GHz and referenced to the input of the waveguides.

It is evident that the coupling coefficient (in dB) decreases linearly with increasing the distance between the slots. This behavior might be attributed to small electrical size of the radiating slot. For circular resonant slot of Figure 1(a), the electric field is more concentrated around the gap between the conducting strips. Consequently, there is such a small area over which the interaction between the slots significantly dominates the coupled power from the other areas.

In fact, the behavior of the mutual coupling of the circular resonant slot seems to follow exponential trend as indicated in Figure 5 (α=1/2.7, β=6.25x10^{-5}). This behavior is distinct from the typical $1/D$ behavior observed previously for the rectangular slots [3, 5].

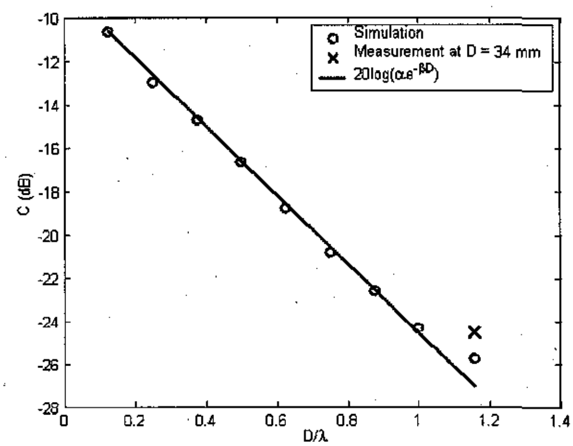


Figure 5: Normalized coupling coefficient between the two slots for the E-plane case.

4 CONCLUDING REMARKS

Circular resonant slots are attractive array elements which can be used in the design of compact imaging arrays. In this paper, the mutual coupling between such slots was numerically and experimentally investigated. The mutual coupling in the E- and H-plane configurations of two identical slots was analyzed. Higher coupling between the slots was observed for the E-plane array compared to the H-plane case. It was shown that, for edge-to-edge interspacing as small as

0.1λ, the mutual coupling is less than -10 dB. Furthermore, the behavior of the mutual coupling of the circular resonant slot was shown to follow exponential trend.

ACKNOWLEDGMENT

The funding for this work was provided by a grant from the NASA Marshall Space Flight Center (MSFC), Huntsville, AL.

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MSFC-207.

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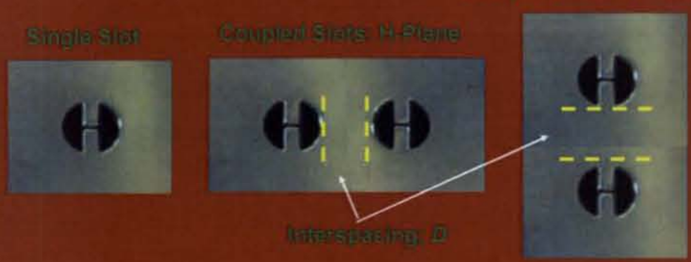
Motivation

- Array of circular resonant slots can be utilized for near- and far-field microwave imaging purposes.
- The high sensitivity associated with a circular slot at its resonant frequency and its small physical size are major advantages over other elements.
- For high resolution imaging applications, large arrays of closely spaced circular resonant slots can be used (sub-λ/2 Spacing).
- Mutual coupling (MC) among the slots can adversely impact the sensitivity and dynamic range of an imaging system.
- The objective is to assess the MC between such type of slots.

Methodology

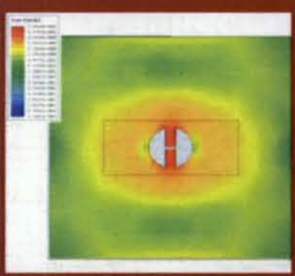
- Slot construction is based on loading an inductive circular slot by a capacitive load (i.e., the gap between the extended strips).
- Numerical (i.e., HFSS based) and experimental analysis of the MC between two slots fed by rectangular waveguides.
- Mutual coupling in E-Plane and H-Plane configuration is considered.



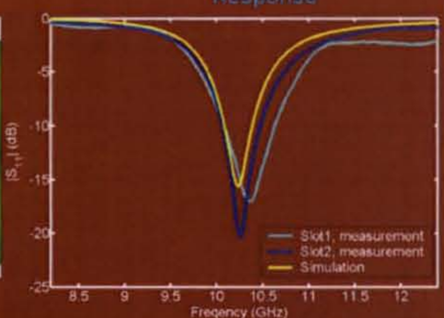
Single Slot

Circular resonant slot of diameter 15 mm and air gap width 0.46 mm.

Current Distribution

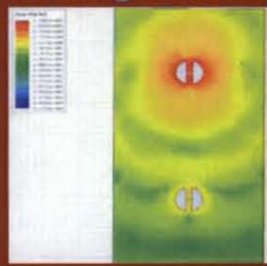


Measured & Simulated Response

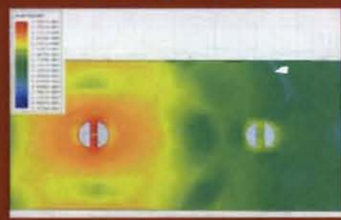


Coupled Slots

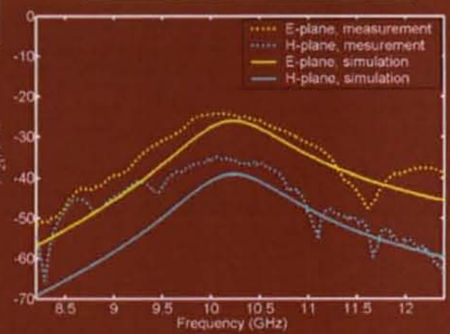
E-Plane @ 10.24 GHz

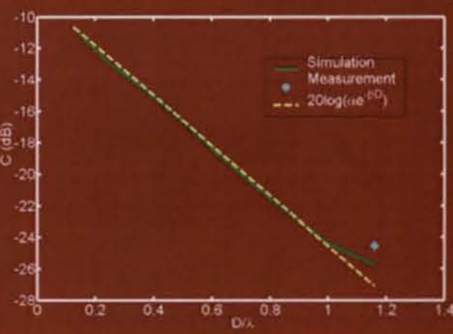


H-Plane @ 10.24 GHz



Measurement vs. simulation for coupled E- and H-plane slots with interspacing of 34 mm





Normalized coupling coefficient between the two slots as a function of slots interspacing for the E-plane case

$$C = 10\log\left[\frac{|S_{21}|^2}{(1-|S_{11}|^2)(1-|S_{22}|^2)}\right] \text{ (dB)}$$

Summary

- ✓ The mutual coupling in the E- and H-plane configurations of two identical circular resonant slots was analyzed.
- ✓ Higher coupling between the slots was observed for the E-plane array compared to the H-plane case.
- ✓ It was shown that, for edge-to-edge interspacing as small as 0.1λ, the mutual coupling is less than -10 dB.
- ✓ The behavior of the mutual coupling of the circular resonant slot was shown to follow exponential trend.

Acknowledgment

This work was funded by a grant from the NASA Marshall Space Flight Center, AL, USA.